MOTORBOOKS WORKSHOP

MODERN MOTORCYCLE TECHNOLOGY

Massimo Clarke

HOW EVERY PART OF YOUR MOTORCYCLE WORKS

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TYPES AND USES

A motorcycle can be divided into two parts, the "motor," meaning the engine and transmission, and the "cycle," composed of the frame, suspension, wheels, and brakes. In the past, all motorcycles were fundamentally quite similar despite the variety of uses for which they were made. Sport models were nothing more than faster versions of the basic model (using the same frame, suspension, and so on), perhaps with slight variations on the aesthetic level. The same applies even for models made for off-road use. Gradually, however, motorcycle models became more specialized, and today each motorcycle type sharply differs from the others in terms of appearance and also in terms of mechanics and features.

Naked (sometimes called "standard") motorcycles are without fairing, leaving the mechanics visible. Put to a wide variety of uses, they are as suitable for daily city use as for use on open roads, even trips. Indeed, they do not perform poorly if put to decidedly sporting uses. All told, they are versatile and multi-use to the point that they reach excellent speeds on race tracks. The frame is often of tubular construction and in some cases has a trellis structure. Standards usually have 17-inch wheels and a good braking system. The handlebars, whether low or medium in height, are almost always more or less straight.

Sportbikes are high-performance motorcycles typically with fairings.

The technical refinements of a modern high-performance motorcycle, such as this four-cylinder MV Agusta, are reflected in the complexity of the engine packaging.

Sportbikes like this GSX-R1000 put the rider in a racing position and are equipped with brakes and suspension systems worthy of a competition bike.

In recent years this category has come to include even higher performing bikes called superbikes, some of which can be considered street-legal race bikes, since only minimal modifications are necessary to ready them for racing. Sportbikes are designed for performance, not comfort, with the rider positioned low behind the windshield; the foot pegs are high and set back to the rear, and the clip-on handlebars are minimally adjustable. The "cycle" geometry (angle of the head tube, trail, and so on) put a premium on handling precision. Sportbike engines offer astonishingly specific power, and both the suspension and braking system are the best available on the motorcycle-parts market.

Superbikes are directly derived from the large-engine sportbikes. These are the champions on race courses all over the world.

An interesting segment of the motorcycle market is composed of machines designed for long-distance touring. These are made to accommodate two riders and offer cargo space along with notable comforts and excellent wind and weather protection.

The Kawasaki GTR 1400 is an excellent example of the sport tourer category of motorcycles, made for comfort and provided with accessories and bodywork to shield both driver and passenger.

Two of the major appeals of standard motorcycles are their versatility and practicality. This is a BMW R1200R.

For several years, large adventure-touring bikes like this powerful KTM 990 Adventure S have been popular with riders, to whom they offer excellent performance on both asphalt and off-road.

Numerous superbike competition machines are based directly on 1,000cc four-cylinder sportbikes, represented here by this Yamaha R1.

For cruisers, with their custom-style aesthetics, nothing is better than a large-displacement V-twin engine, often air cooled. Harley-Davidson is the king of this market.

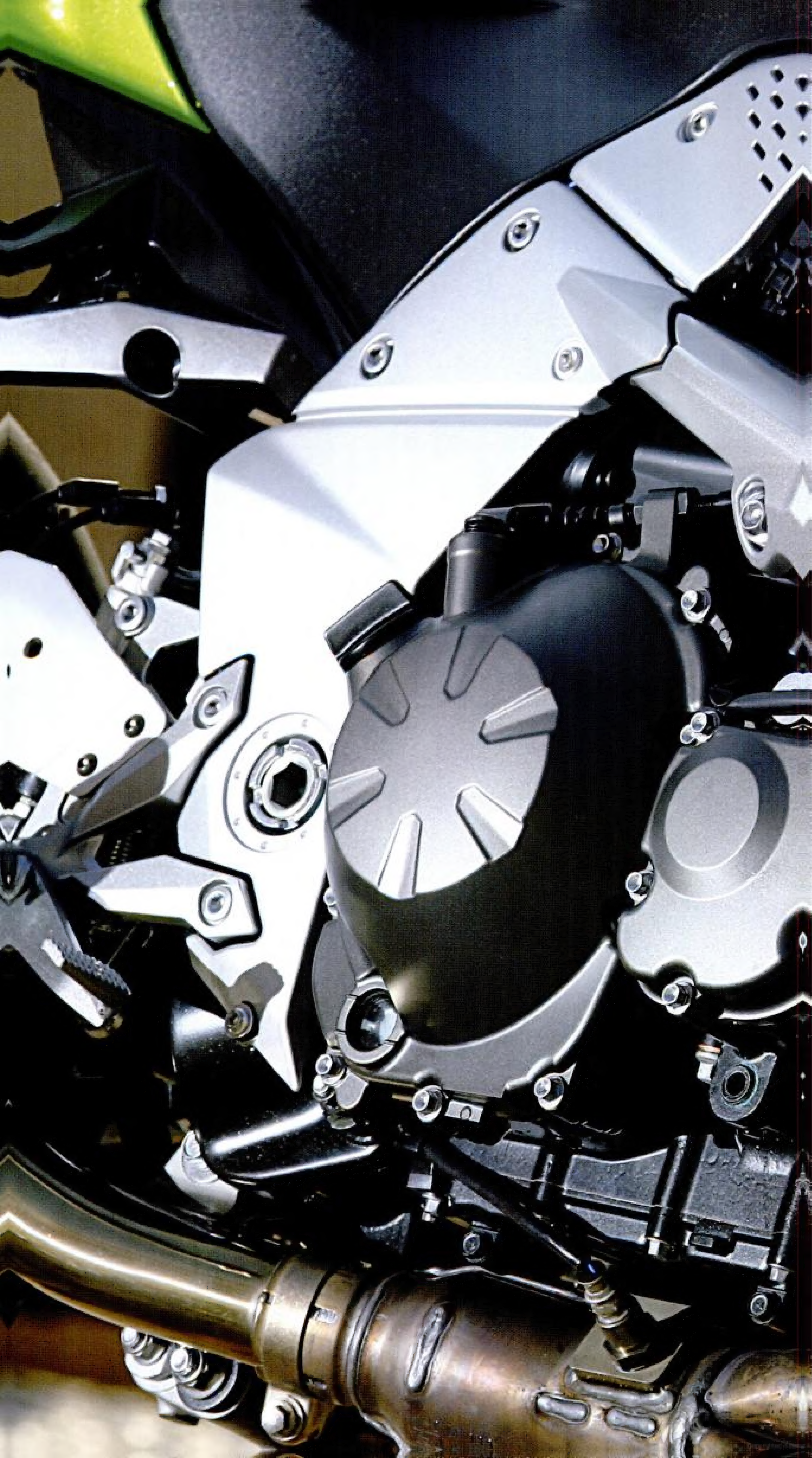
With its modern technology on full display, this two-cylinder Morini is a beautiful example of a modern standard-style motorcycle.

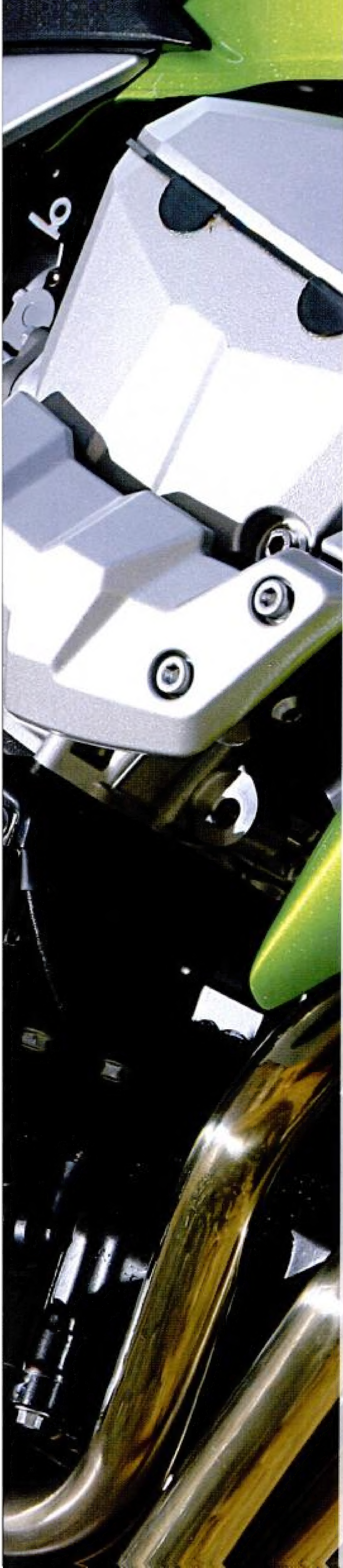
These models are comfortable to ride and feature large fairings to provide protection for the rider, making them good in the rain. The handlebars are taller than on a standard machine and the large saddle is well shaped and padded; creature comforts are designed down to the smallest detail. In many cases the grips are electrically heated so they can be more comfortably used at low temperatures. Touring bikes are often large, with a generous wheelbase, so they tend to be heavy.

Enduro bikes, originally designed for use in off-road events, are all-terrain bikes that have long been popular for their great versatility and ease of handling. They are, in fact, suitable for a wide range of uses, from daily street riding to touring with two people and baggage to riding on dirt roads, sand, or even on off-road routes, provided these are not too demanding. Enduros usually have wire wheels, narrow, slightly raised handlebars, and a comfortable, upright position for the rider. The suspension system offers lengthy travel, the front wheel is usually 19 or 21 inches, and the trail dimension is often long. Enduro engines typically have one cylinder (if the displacement is less than 650 cc) or two.

Cruiser bikes originated with certain American models of the 1950s and 1960s. Their characteristics include a longer, more raked fork, long trail, a stretched-out position for the rider with forward-mounted foot pegs, sometimes very high handlebars, and, in some cases, extended seats with a small backrest. The engines are usually V-twins that have relatively modest outputs compared to their displacement size, but offer high torque at low rpm and an unmistakable sound. Cruisers might have wire or cast wheels. The wheelbase is invariably long.

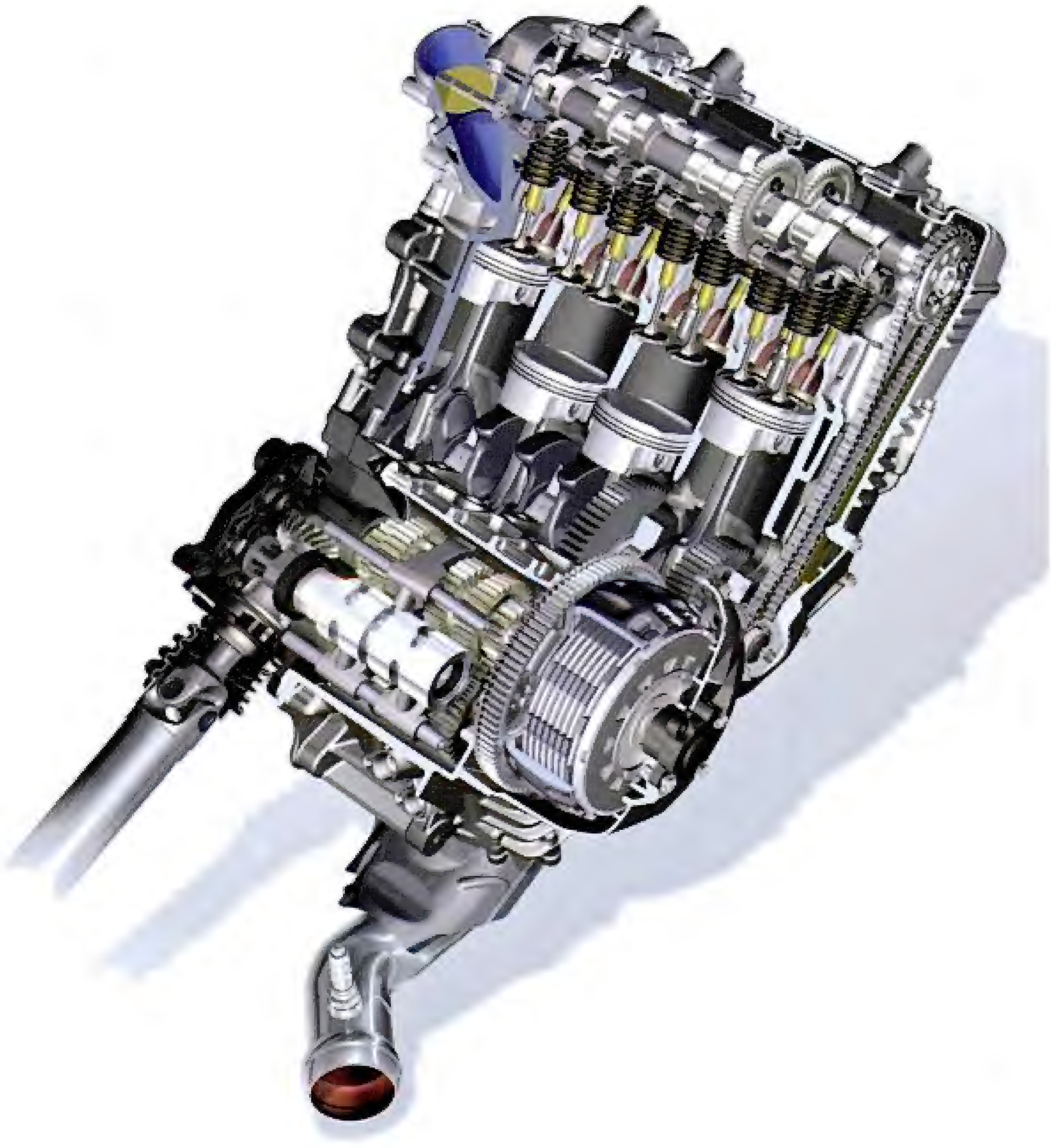
In addition to these main road bike types, there are others, far more specialized, that are designed to serve specific "slices" of the market. They include supermotard bikes, competition off-road bikes, retro-style motorcycles, mini bikes, adventure touring bikes, choppers, and all those machines that are not road-legal, having been made specifically for roadracing and motocross.





The Engine

STRUCTURE AND FUNCTION

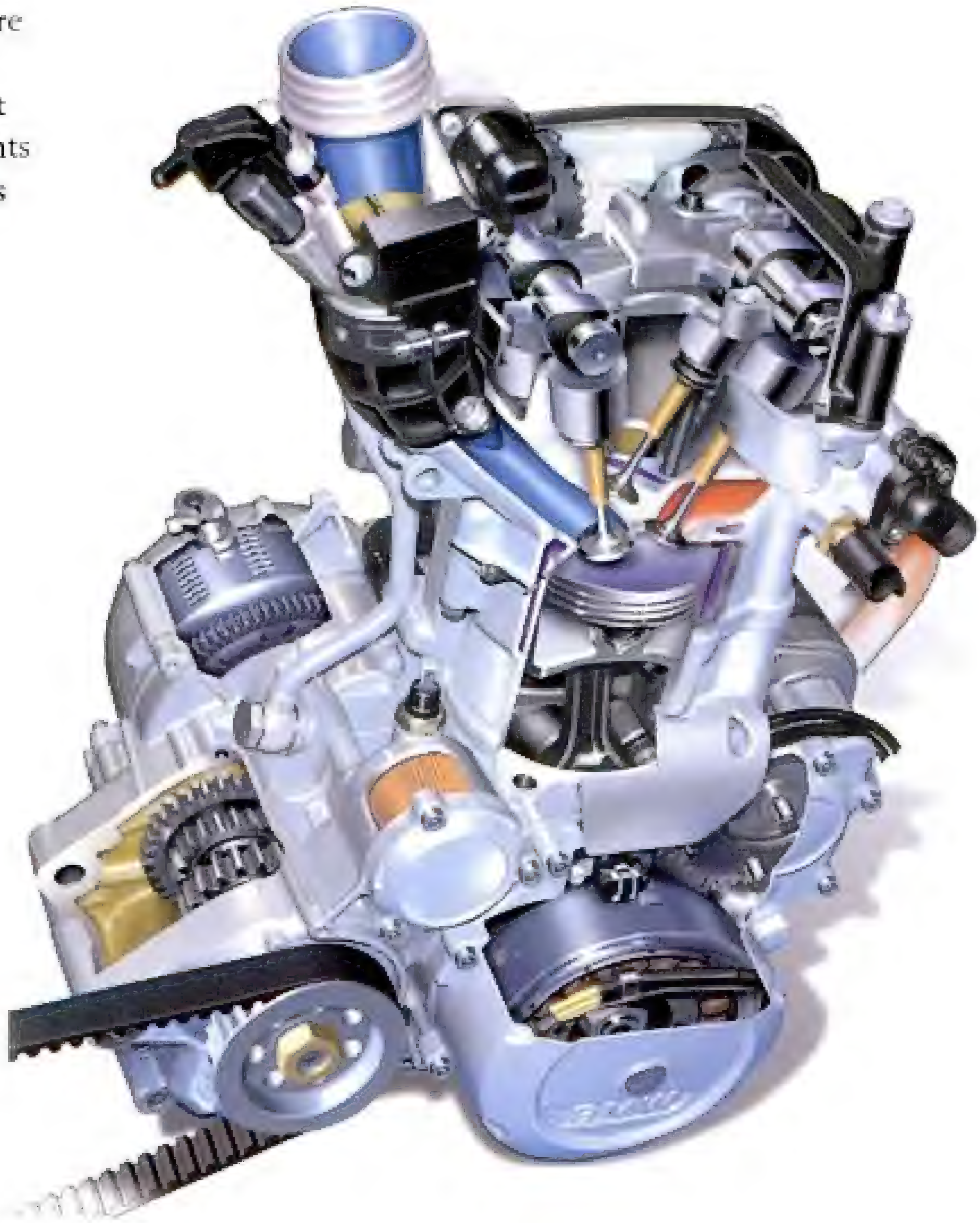


Modern motorcycles are most typically powered by four-stroke engines using spark ignition, also known as Otto-cycle engines after their inventor, Nikolaus August Otto. (The name also applies to two-stroke engines.) The fuel powering most bikes is gasoline, though a few countries use ethanol instead. Two- and three-wheeled vehicles powered by modest-performance diesel engines derived from industrial uses have been made in India, but they are mentioned here only as a curiosity.

The logical structure of BMW's modern high-performance inline four-cylinder engine is clearly visible in this illustration (BMW).

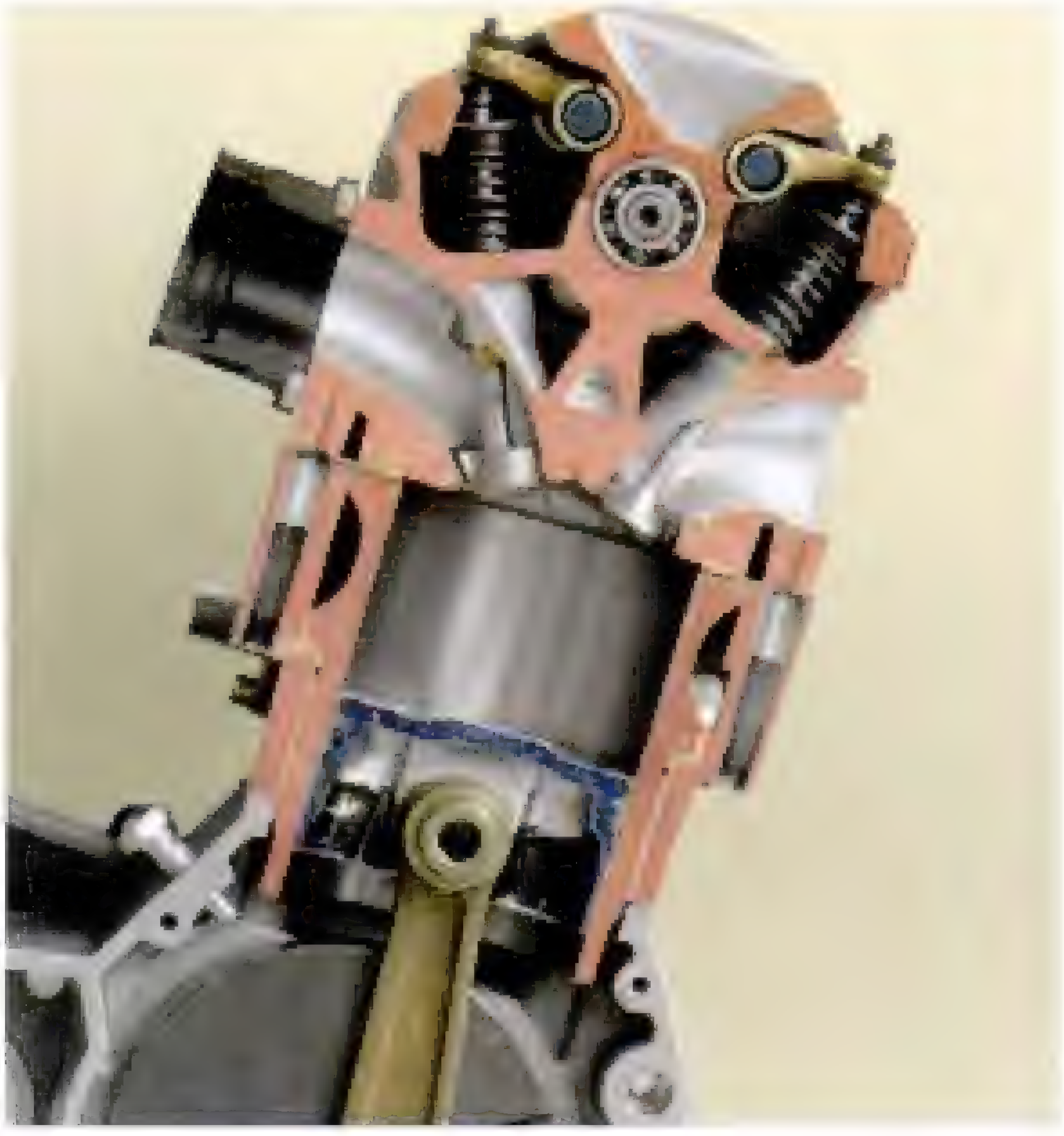
In giving a schematic description of a typical four-stroke motorcycle engine, we will make reference, for the sake of simplicity, to a vertical single-cylinder with only two valves. The structure is composed of both fixed and moving parts. First among the fixed parts is the crankcase, which houses the rotating

Single-cylinder engines are more compact and simpler from the construction point of view. This image highlights the arrangement and shapes of the components inside BMW's single (BMW).

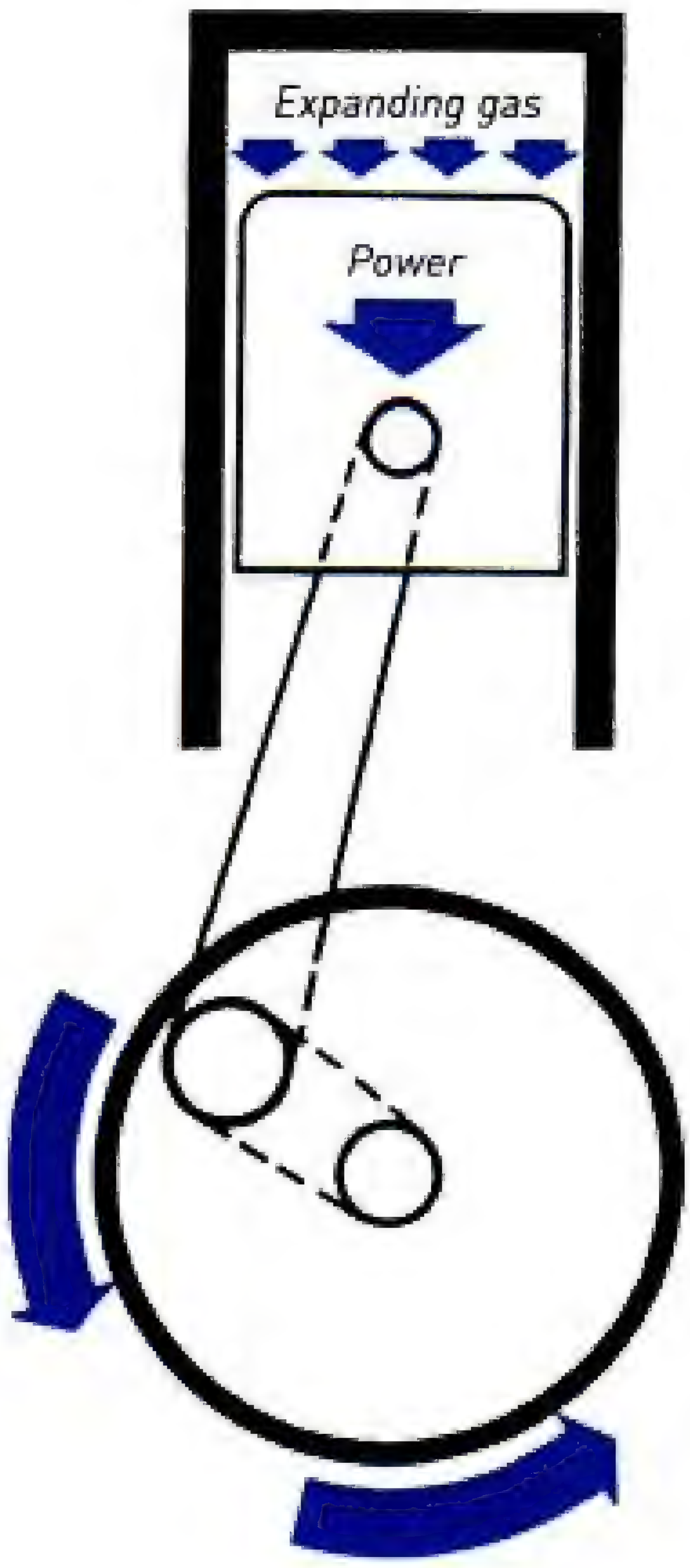


Basic Engine Terms

BDC—Acronym for bottom dead center, meaning the position at which the piston is located nearest the crankshaft. If the cylinder is vertical, it is the lowest position the piston reaches inside the cylinder. When it reaches BDC, the piston stops briefly before beginning to travel in the opposite direction, toward TDC.
Bore—The diameter of a cylinder opening, usually expressed in millimeters.
Compression ratio—When the piston rises to TDC, after having drawn the air/fuel mixture into the cylinder, it presses against the mixture, raising its pressure and temperature considerably. The amount of this compression depends on the ratio between the maximum volume of the piston available for the gases (piston at BDC) and the minimum volume (piston at TDC), as the gases become confined in the combustion chamber: This is the compression ratio.
Displacement—The volume displaced by a piston in its movement from one dead center to the other, expressed in cubic centimeters (less often in liters). The number is obtained by multiplying the area of a cross section of the cylinder by the stroke. It is thus easy to calculate once the bore and stroke of the engine are known.
Engine displacement—Also called "swept volume," this number is obtained by multiplying the displacement of a single cylinder by the number of cylinders in the engine.
Stroke—The distance, expressed in millimeters, between the two extreme ends, or dead points, reached by the piston in the course of its movement inside the cylinder.
TDC—Acronym for top dead center, meaning the position at which the piston is located farthest from the crankshaft. If the cylinder is vertical, it is the highest position the piston reaches inside the cylinder. When it reaches TDC, the piston stops briefly before beginning to travel in the opposite direction, toward BDC.



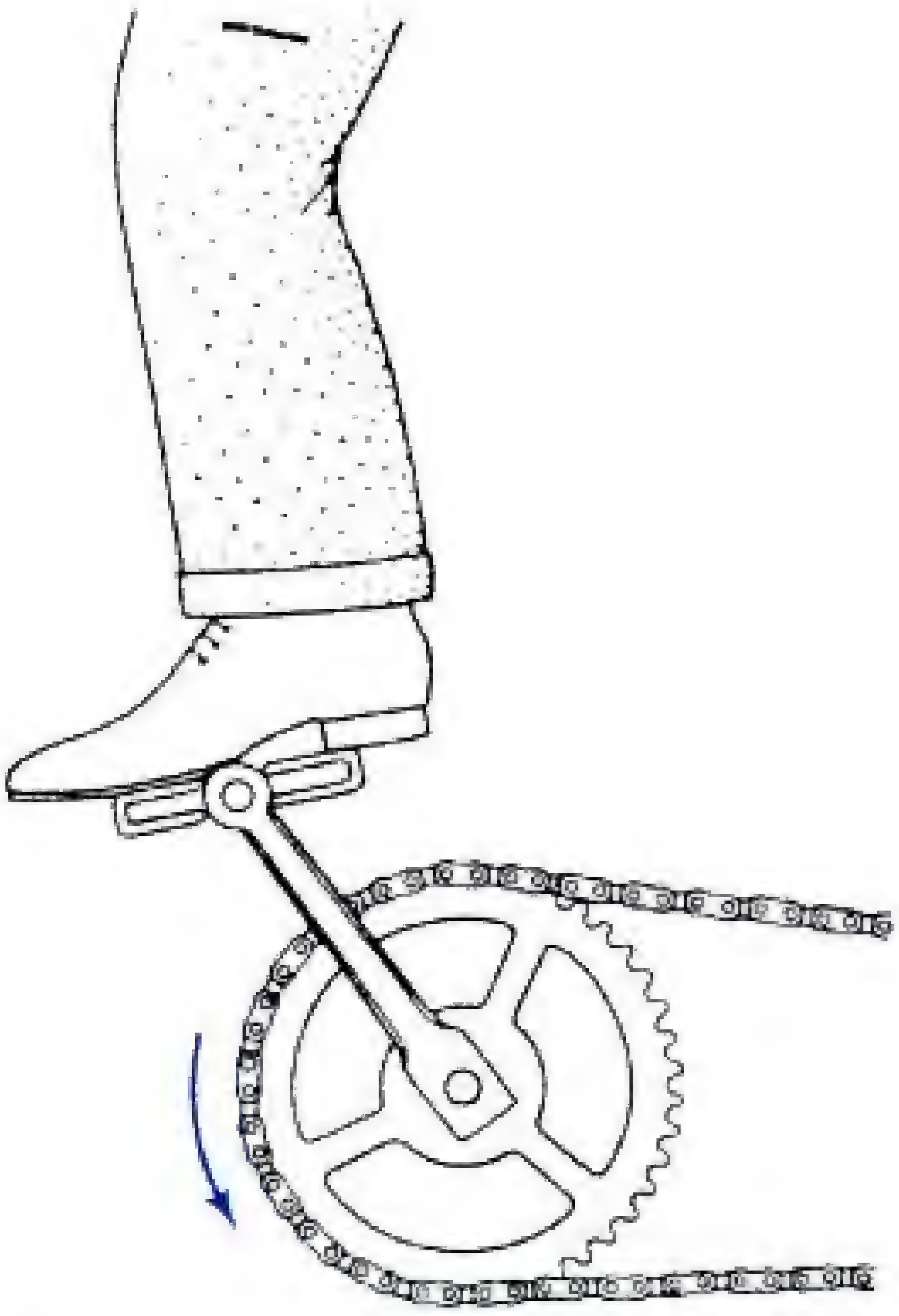
The piston moves up and down in the cylinder during the four strokes of its cycle. This side view shows the arrangement of the valves and ports in the cylinder head.



In the four-stroke sequence, the power stroke is that of expansion, during which the gases drive the piston down. The piston is connected to the crankshaft by the connecting rod (Honda).

parts of the engine like the crankshaft as well as the bearings that support the crankshaft. There is then the cylinder, fixed above the crankshaft and mated to the head. Inside the head are the valves with their respective springs and the other parts involved in their movement. Also in the head are the combustion chamber and the openings for the intake and exhaust valves. The internal surface of the cylinder is the liner, and inside the piston moves up and down.

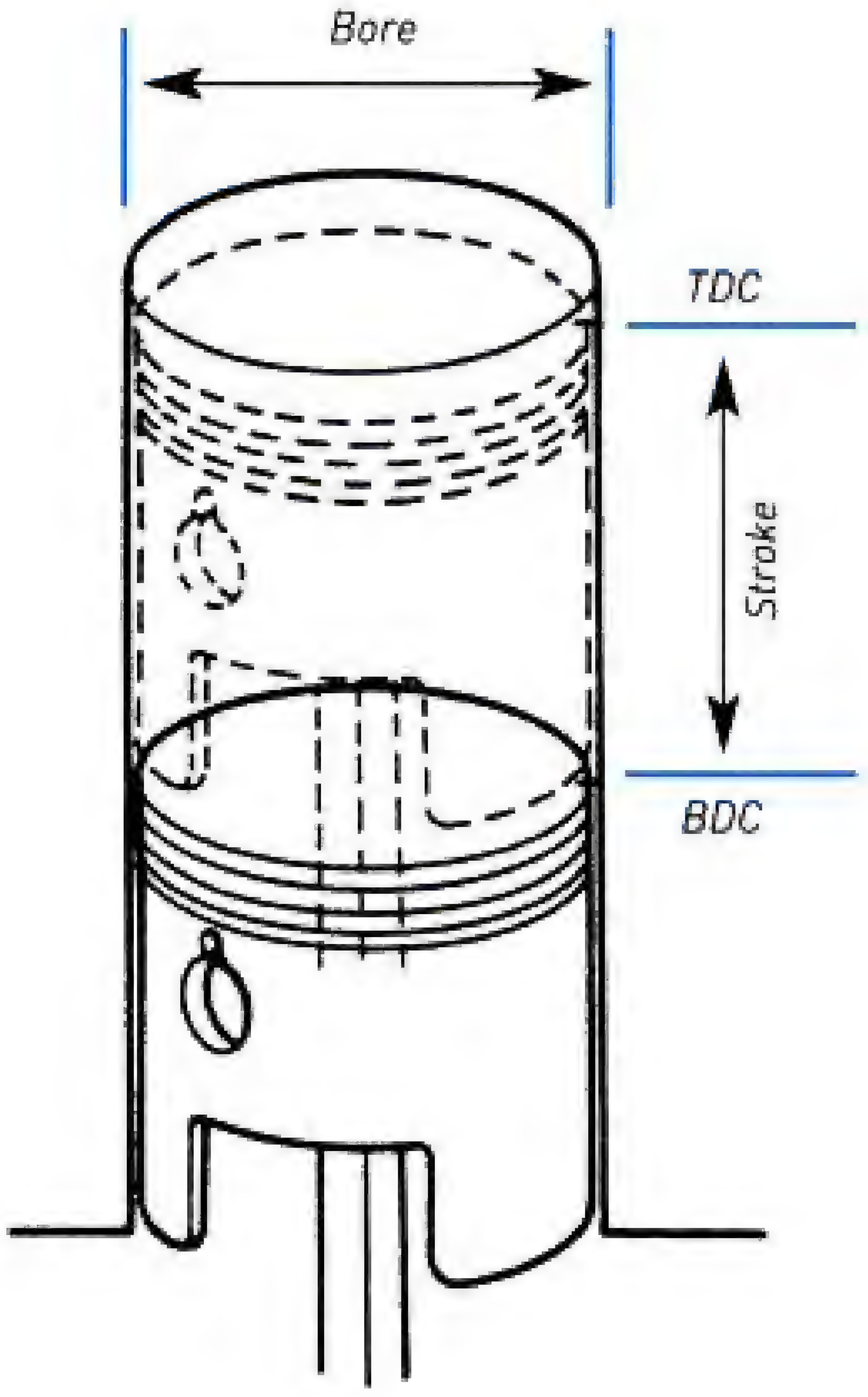
As noted above, located inside the fixed parts are the moving parts. These are the crankshaft with its connecting rod, the piston, and the parts of the valvetrain (valves, camshafts, rocker arms, or tappets). The big end of the connecting rod is connected to the crankpin of the crankshaft by way of a bearing, and the connecting rod small end is connected to the piston via a tubular bearing called the wristpin. The movements of the valves permit or prevent the passage of gases. The intake valve opens during the intake stroke admitting fresh fuel/air mixture, while the exhaust valve opens during the exhaust stroke, permitting the



The connecting rod operates on the crankpin the way a leg acts on a bicycle pedal; the up-and-down motion of the rider's knees is transformed into the spinning movement of the bicycle's sprocket (Honda).

expulsion of burnt gases from the cylinder. During the compression and combustion strokes, both valves are closed.

The structure of two-stroke engines is similar, but the head is reduced to a sort of simple cover since it does not house any moving parts and does not "host" the intake and exhaust valves. Instead, the walls of the cylinder have a series of openings, called ports, for intake, exhaust, and transfer.



Bore is the diameter of the cylinder, and stroke is the distance between the two end points reached by the piston as it moves inside the cylinder (Suzuki).

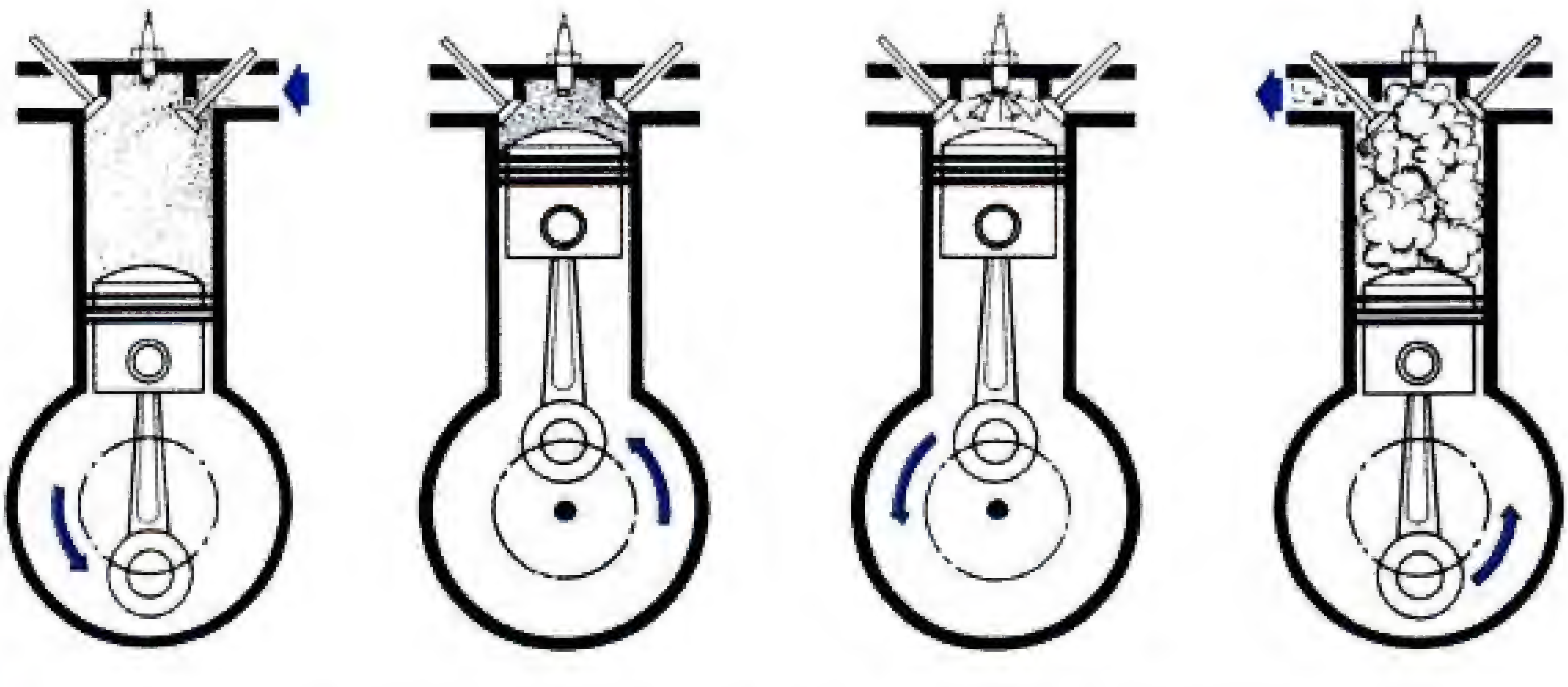
The Four-Stroke Cycle

The engine performs a sequence composed of four strokes, each stroke being the action of the piston traveling the full length of its cylinder. The four strokes are intake, compression, combustion, and exhaust. In the case of a four-stroke engine, these strokes are performed in two revolutions of the crankshaft, or in 720-degrees rotation. The sequence takes place as follows:

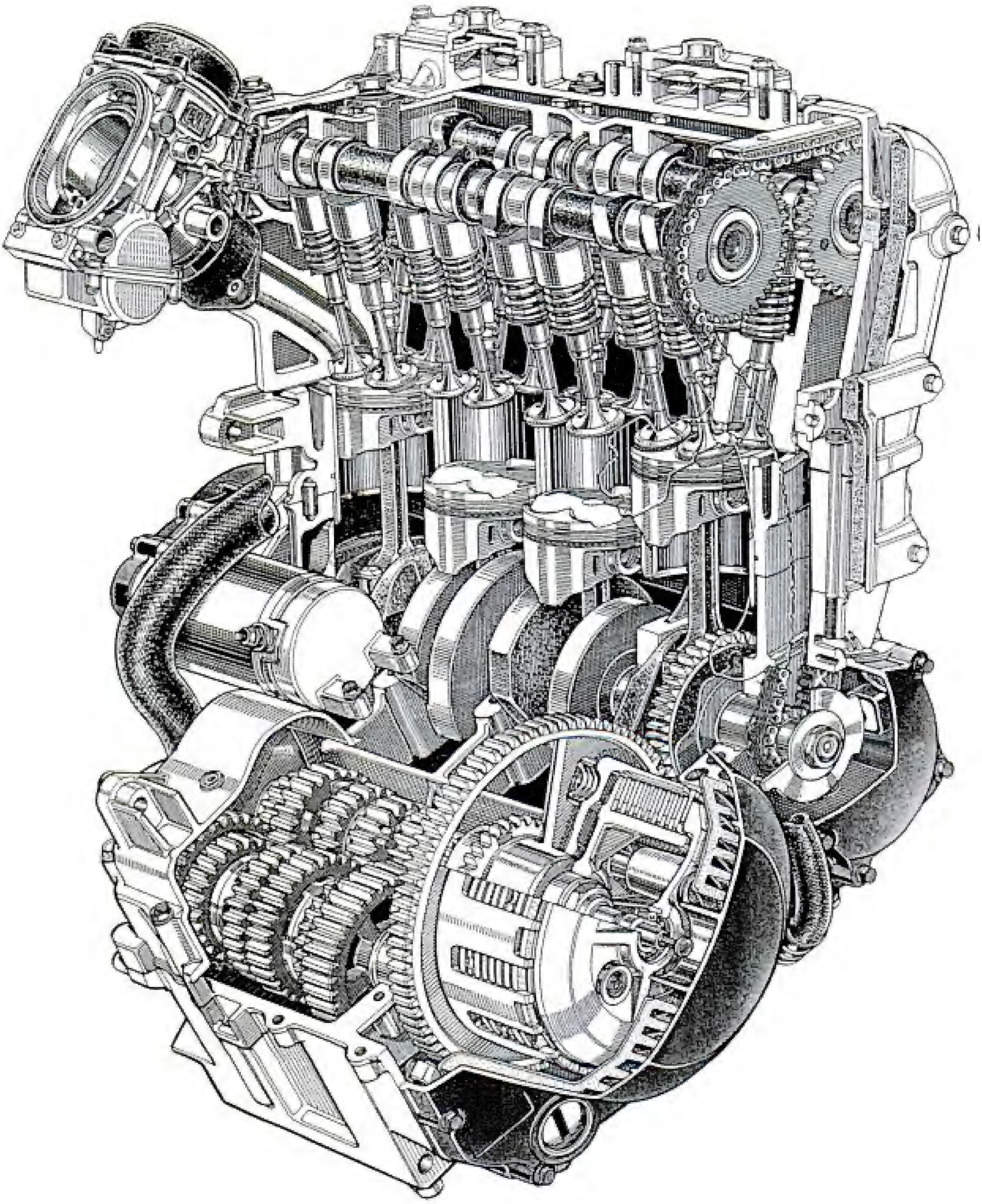
Intake: The down-stroke of the piston, moving from top dead center (TDC) to bottom dead center (BDC), creates a vacuum in the cylinder that draws air/fuel mixture into the cylinder through the intake tube (the valve of which has opened).

Compression: On the up-stroke of the piston, moving from BDC to TDC, the air/fuel mixture is compressed. At the end of this stroke the pressure and temperature of the air/fuel mixture (trapped in the combustion chamber) reaches values on the order of more than 20 bar of pressure and 380 to 500 degrees Celsius.

Combustion (power stroke): At the end of the compression stroke, as the piston nears TDC, an electric spark flashes between the electrodes of the spark plug and ignites the air/fuel mixture, thus beginning combustion. This causes the development of a tremendous amount of heat and also a strong rise in



The sequence of the four-stroke engine. From left: intake, compression, combustion, exhaust.



This drawing presents the shape and arrangement of the various parts that compose a four-cylinder inline engine with twin camshafts. Also visible is the primary transmission with gears, the multidisk clutch, and the gearbox (Kawasaki).

the temperature and pressure in the cylinder. In a contemporary, high-performance four-stroke engine the pressure can reach past 85 bar. During the combustion stroke the piston is forced down to BDC by the pressure of the gas. This is the only power stroke of the four-stroke cycle and now is when mechanical energy is supplied to the crankshaft.

Exhaust: After reaching BDC at the end of the combustion stroke, the piston again rises to TDC, expelling the burnt gases from the cylinder, for which the exhaust valve opens, permitting release of the gases.

The Two-Stroke Cycle

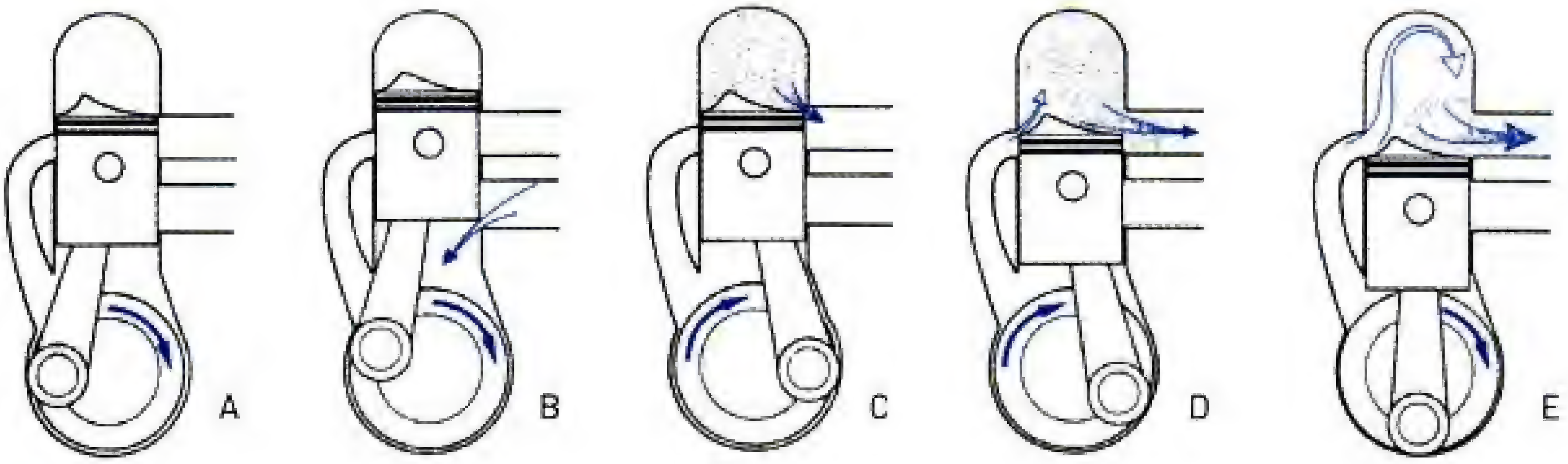
Today, four-stroke engines dominate the field of motorcycles. Two-stroke engines are largely confined to mopeds

The structure of two-stroke engines, which today have only a modest and limited use, is very different from that of their four-stroke cousins (Aprilia).

and small-engine scooters along with a few competition machines (Grand Prix motorcycles of 125 and 250cc and various off-road bikes).

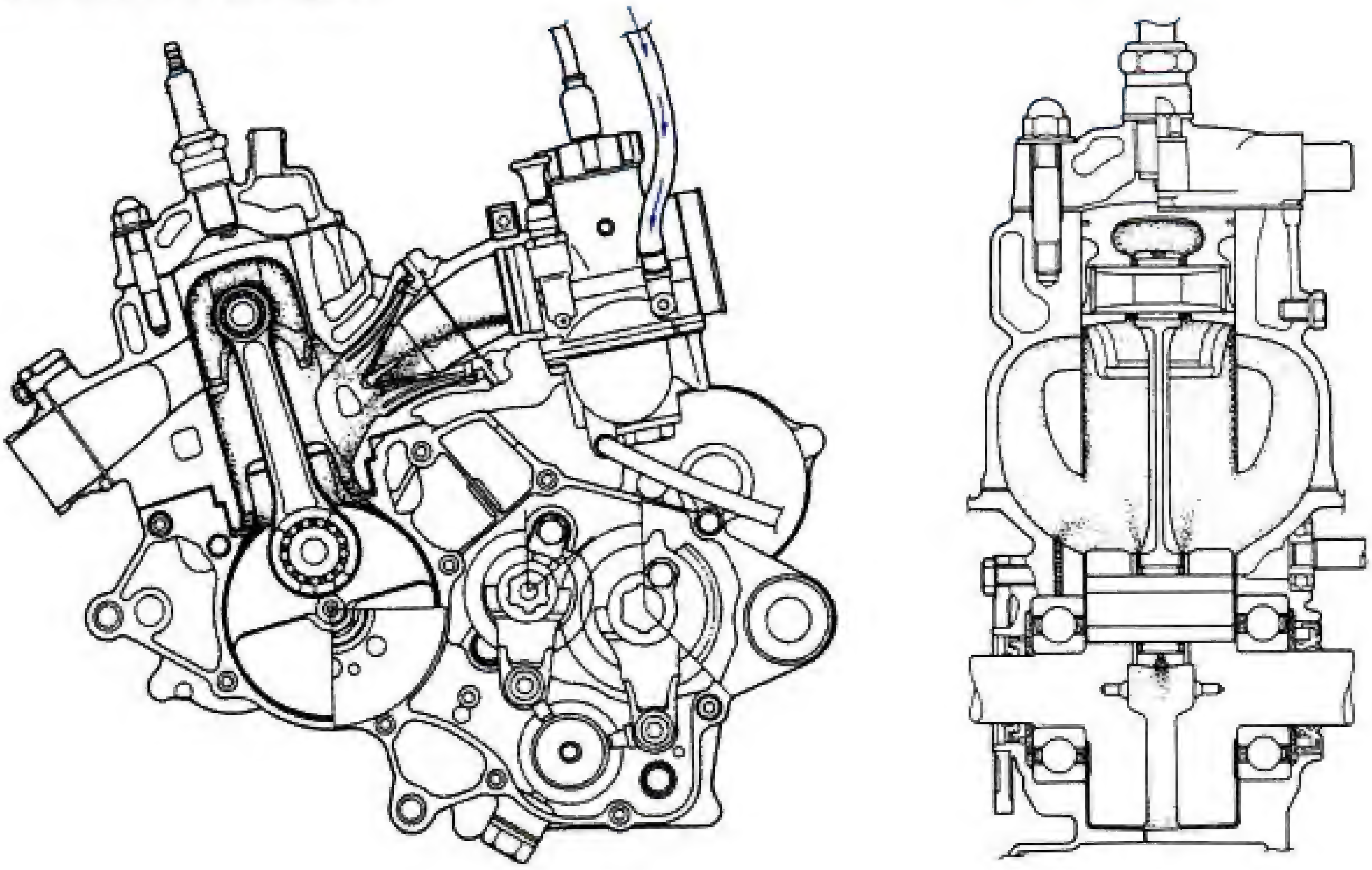
The advantages of two-stroke engines include their mechanical simplicity, their compactness and limited weight in relation to displacement, and the enormous specific power they can deliver. The drawbacks are high fuel consumption in relation to power delivered and exhaust emissions so high that these engines are rendered unacceptable unless adapted to a direct-injection system. They also tend to have shorter life spans than four-stroke engines.

In two-stroke engines, intake does not take place in the cylinder, but rather in the crankcase in which the crankshaft



The four phases of the sequence of two-stroke engines take place in a single revolution of the crankshaft. Intake takes place in the crankcase. A = compression, B = intake in the crankcase, C = beginning of exhaust (at the end of expansion), D = beginning of transfer, E = transfer in full development.

Simple and Compact



These two views make possible a clear understanding of the mechanical simplicity of two-stroke engines. Since they have a power stroke every turn (rather than every two turns), they can deliver far more specific power than four-stroke engines (Honda).

revolves. After being drawn into this chamber, the air/fuel mixture is sent to the upper part of the cylinder through the transfer port. The engine can thus be thought of as being divided in two parts: the part beneath the piston acts as pump, while the four strokes of the cycle take place in the upper part. Unlike what happens in four-stroke engines, in this case the strokes all take place in a single turn of the crankshaft, meaning 360 degrees of rotation. The cycle takes place as follows:

The piston rises from BDC toward TDC. As the piston rises, a low-pressure area is created in the crankcase that draws in a fresh air/fuel mixture (fresh air from the outside mixed with fuel inside the carburetor). In the upper part of the cylinder, the rising piston shuts off the transfer port and immediately after that the exhaust port (located a little higher) closes. The rising piston progressively compresses the air/fuel mixture that earlier entered through the transfer port.

The piston descends from TDC to BDC. Combustion takes place above the piston, creating pressure that forces the piston downward toward BDC. At a certain point as it moves downward the upper edge of the piston uncovers the exhaust port, and the burnt gases begin to flow out of the cylinder.

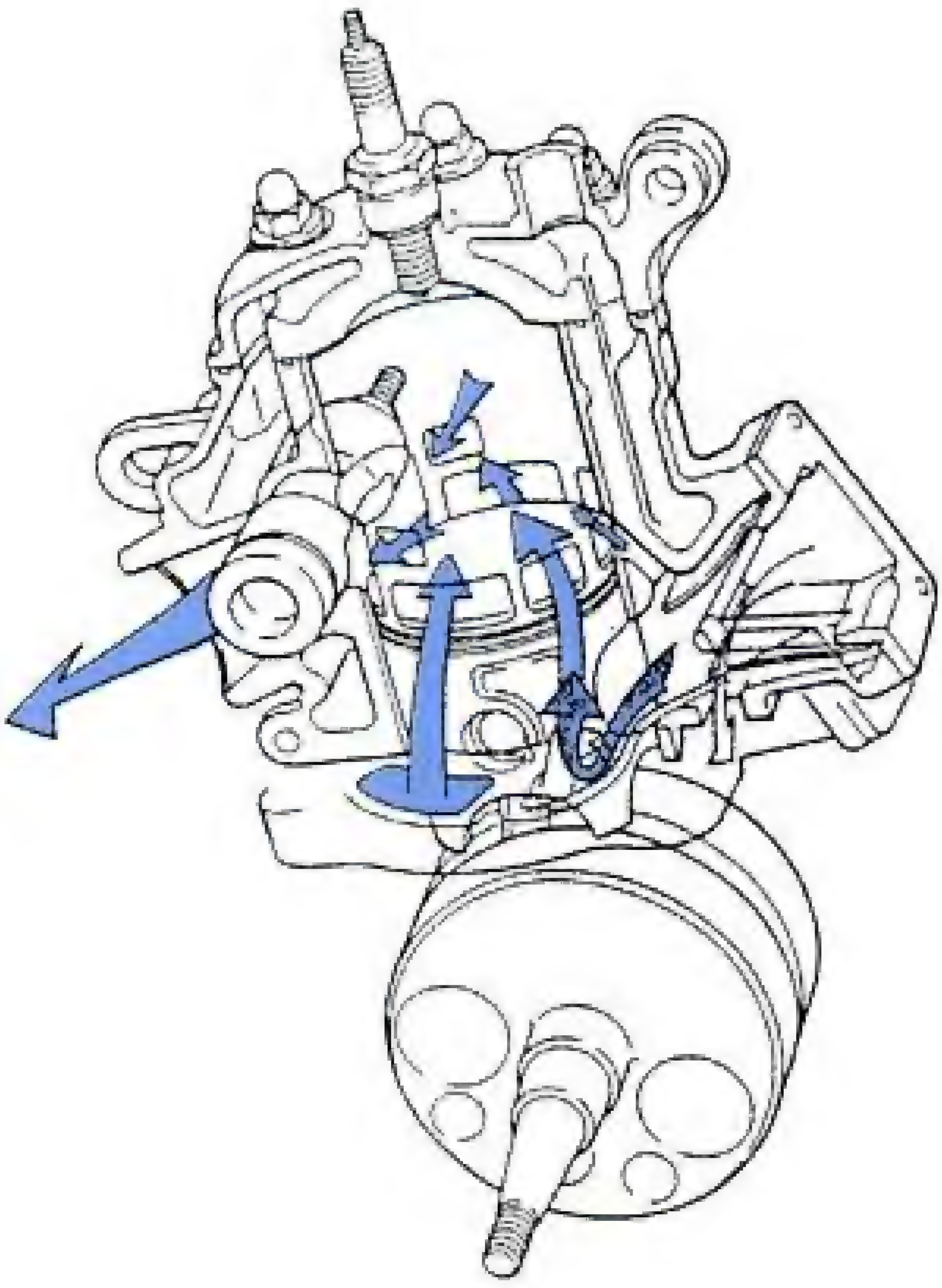
At the same time, the descent of the piston reduces the space available in the crankcase for the fresh gases, resulting in a kind of "precompression." Shortly after this, having moved farther toward BDC, the piston uncovers the transfer port, and the air/fuel mixture rises from the crankcase into the cylinder, where it takes the place of the burnt gases—and to a certain degree contributes to scavenging those burnt gases, for which reason the fresh gases are said to perform a kind of "washing" of the cylinder.

Reed Valves and Transfer Ports

In two-stroke engines, the intake port, which connects the carburetor to the

crankcase, must have a valve (or other system) able to permit or prevent the passage of the fresh air/fuel mixture at the right time in the cycle. If it did not have such a valve, the crankcase could not function as a pressurization chamber for the air/fuel mixture.
An automatic, one-way valve called a reed valve is used in most two-stroke engines. In some competition models a rotary disk valve is used instead.
The number and arrangement of the transfer ports are very important in terms of engine performance. There are usually five of these (four larger ones on the sides, "of delivery," plus one of "correction" located opposite the exhaust port).

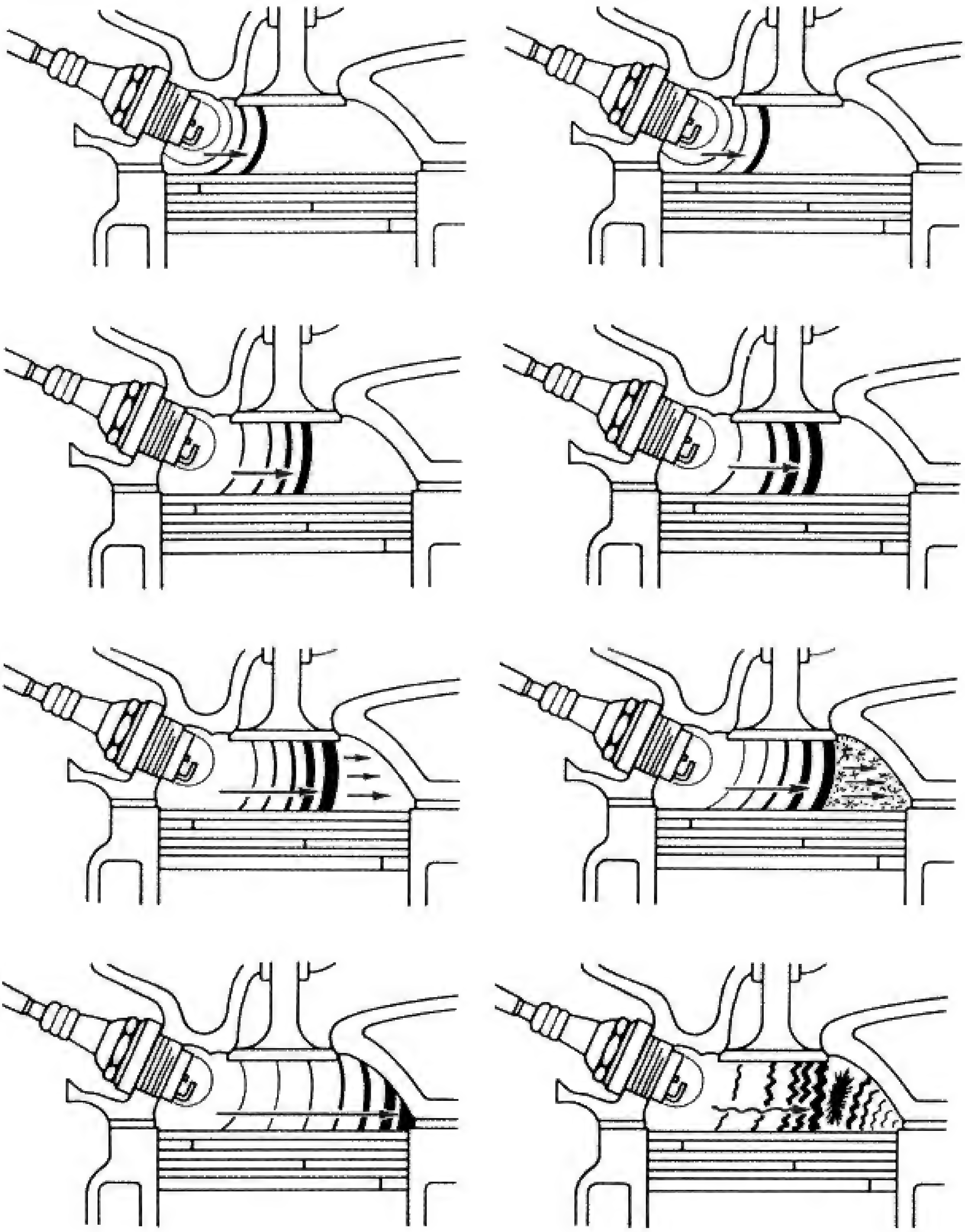
Two-stroke engines were formerly crossflow-scavenged, with transfer and exhaust ports on opposite sides of the cylinder and a deflector atop the piston to direct the intake and discharge. This system has been replaced by loop-scavenging in which transfer ports direct the flow of the gases to the combustion chamber, from where they are deflected downward. Even so, the scavenging is anything but perfect because of the inevitable loss of a considerable amount of the fresh mixture, which leaves the engine with the burnt gases (thus depriving the engine of fuel while also polluting the atmosphere). At the same time, a notable quantity of burnt gases is not expelled and remains inside the cylinder. In high-performance two-stroke engines, great importance is given to fitting them with exhaust valve systems or expansion chambers, which make it possible to best exploit the waves of pressure so as to fill the cylinder with fresh air/fuel mixture.



The arrows indicate the movement of gases during the transfer phase in the cylinder of a modern two-stroke engine (Yamaha).

In almost all of today's two-stroke engines the intake is controlled by a reed valve that functions automatically.

Combustion and Knocking



The four diagrams in the left column give a schematic view of the process of normal combustion. The diagrams on the right present combustion with knocking: before the flame front has reached it, a part of the fresh air/fuel mixture suddenly ignites (General Motors).

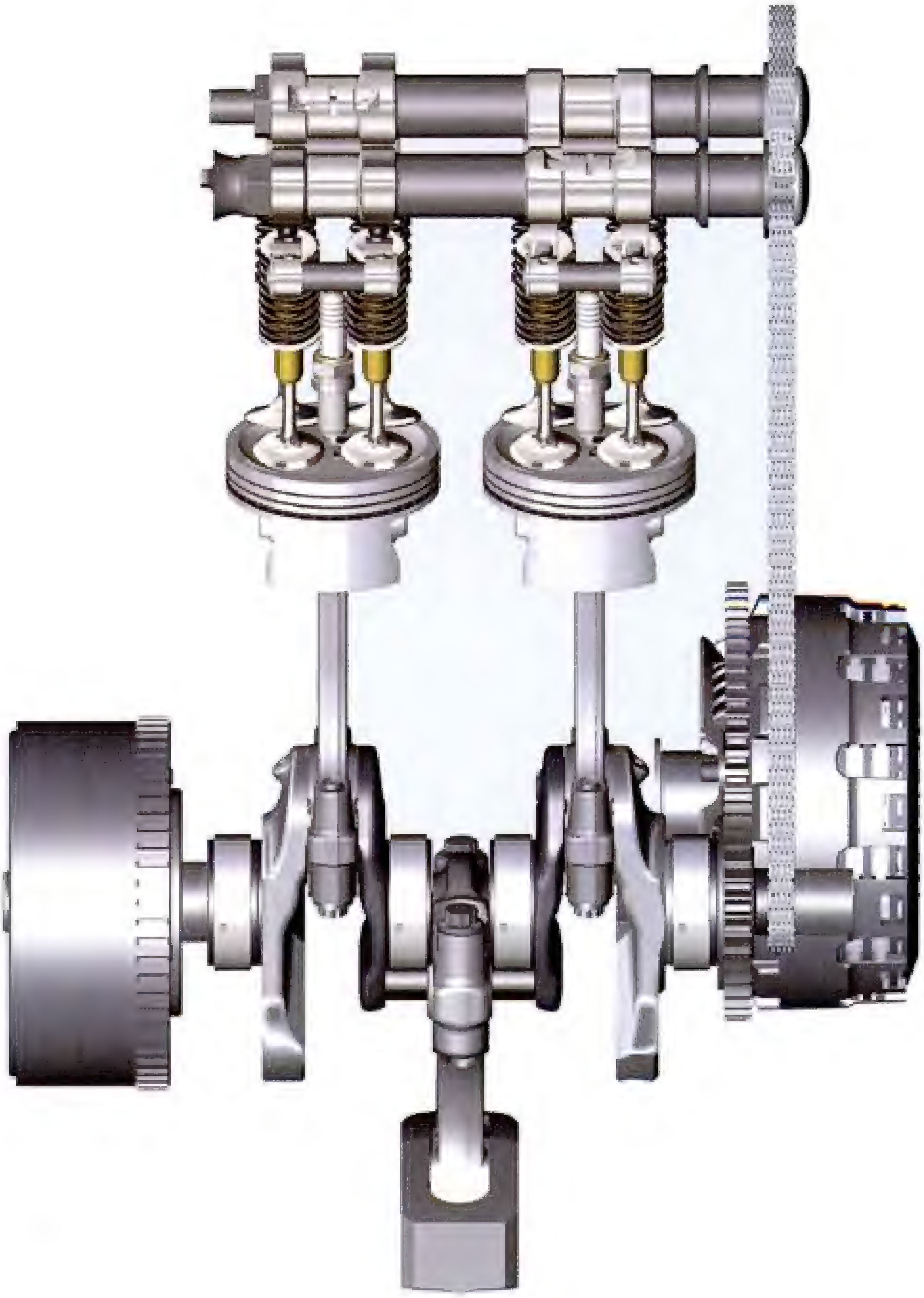
inside the engine grows and thus also the power that, at that given rotation speed, the engine provides. The output changes with variations in engine speed rotation, reaching its highest value at a given rotation speed (that coincides with that at which there is maximum torque), after which it drops in a more or less gradual way.

The shape of the volumetric efficiency curve is determined by the timing of the valvetrain and by the

■ Modern high-performance engines are devices of great technological refinement in which all the components have been designed to obtain the best overall performance (Benelli).

characteristics of the intake and exhaust systems, meaning the configuration and size of the exhaust and ports. One might think that, as with other outputs, the maximum value theoretically obtainable could be established, but that of volumetric efficiency is a case apart. Opportunely exploiting both the energy of the gas columns that travel inside the intake and exhaust systems as well as the waves of pressure, it is in fact possible to reach values slightly greater than 100 percent, in correspondence to certain rotation speeds. In Otto-cycle engines, power output is controlled by acting on the volumetric efficiency by means of the throttle; breathing is perfectly free (and thus the efficiency is highest) only when the throttle is fully open, which happens when the throttle is opened all the way.

ENGINE DESIGN



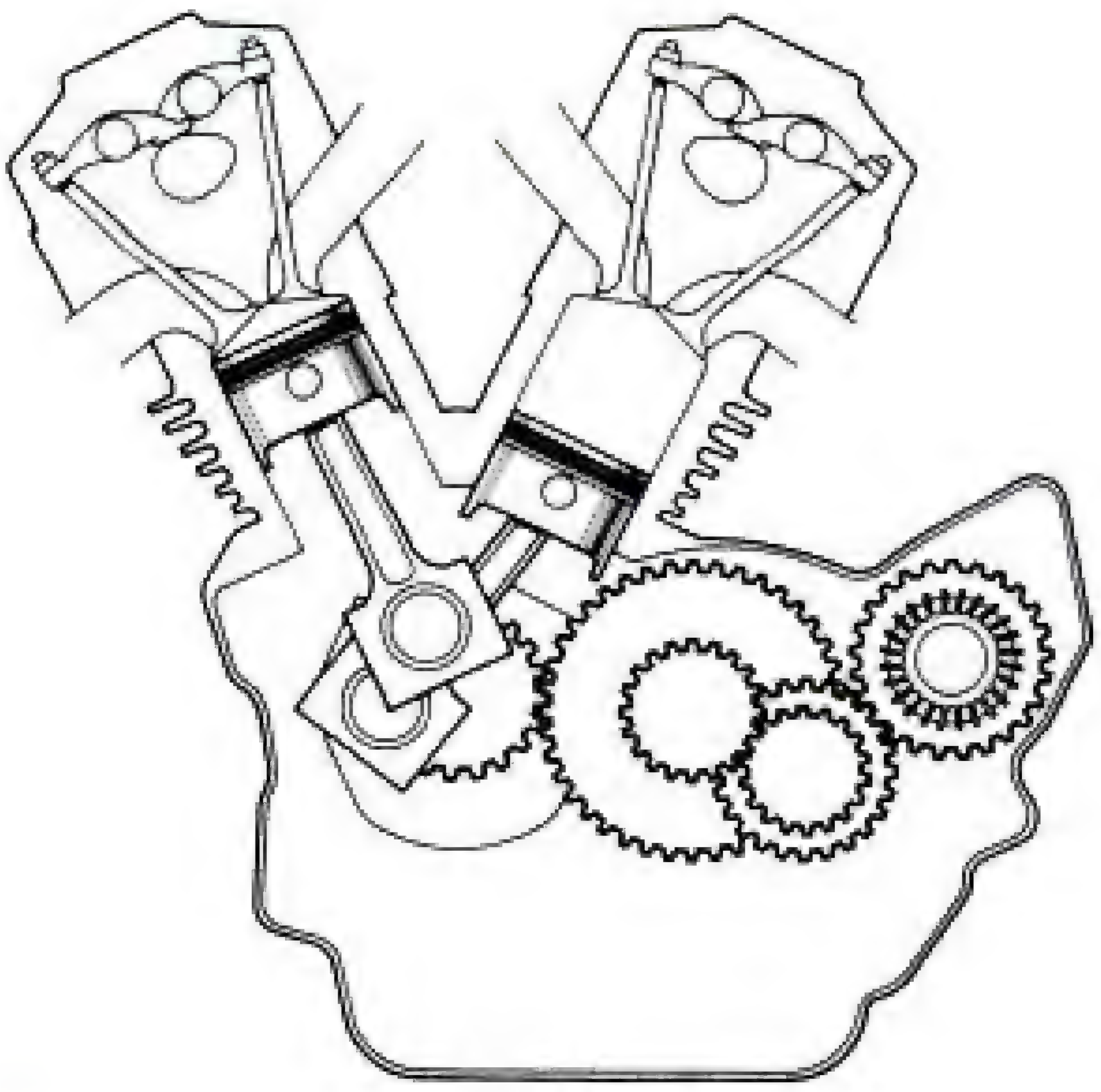
The simplest engines, not surprisingly, are those with only one cylinder. Light and compact in relation to their engine capacity, they cost less to manufacture than multi-cylinder engines since they involve fewer parts and less labor. They dominate the world of small engines as well as the enduro and motocross motorcycle classes (which must be agile and speedy and are thus fitted with engines whose weight and size have

■ The vibrations generated by parallel-twin engines can be eliminated only by using dynamic balancers. Visible here in a central position is the balancer used by BMW on its 800cc engines.

been greatly reduced). Single-cylinder engines are also used by most scooters.

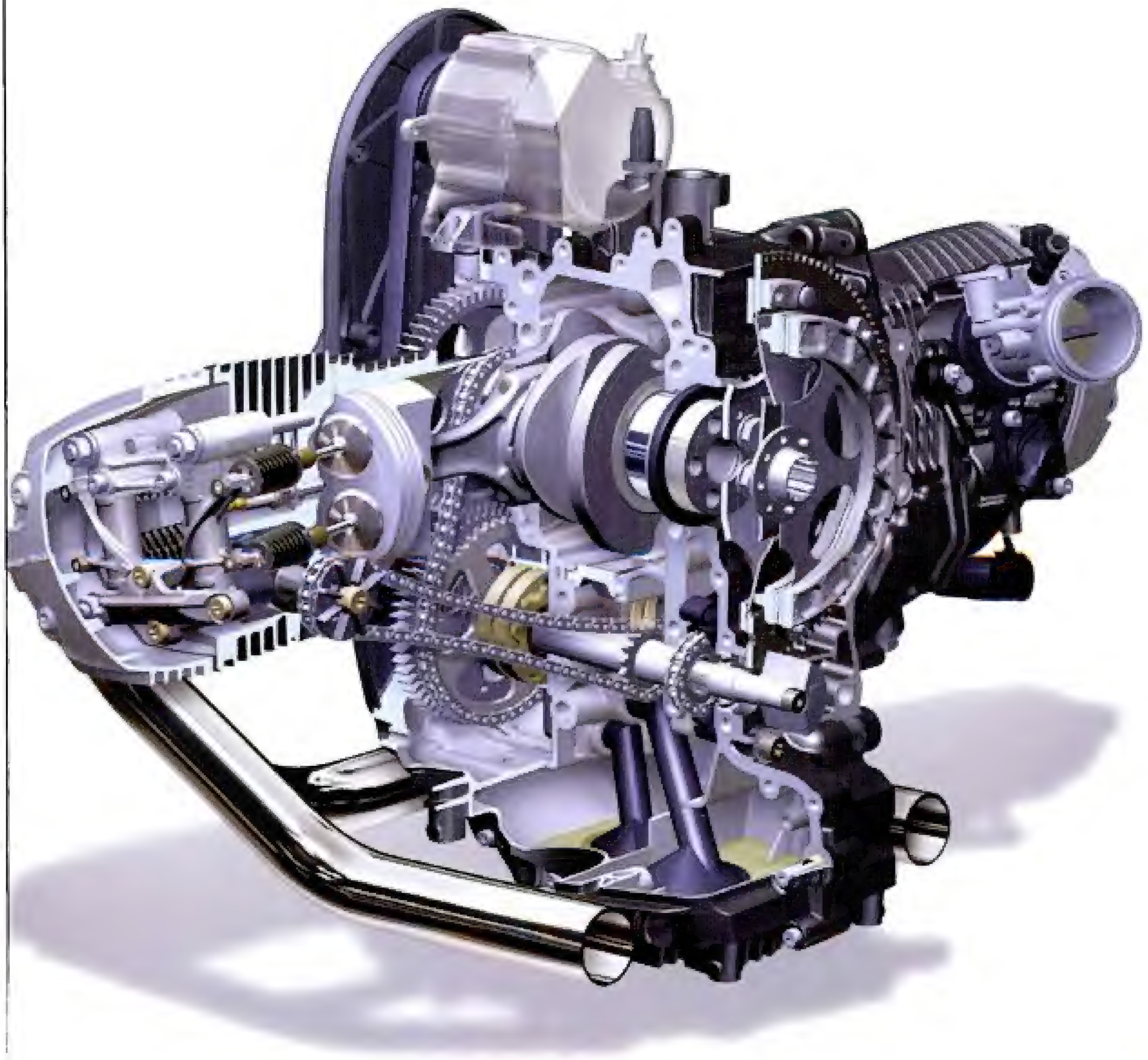
The crankshaft has a single crankpin to which is mounted a single connecting rod, and the crankshaft is typically the

Good balance is obtained in this Honda 52-degree V-twin through the use of a crankshaft with two offset crankpins.



are perfectly balanced), although it is not perfect. Furthermore, if the V is longitudinal, the engine tends to have a considerable length. On the upside, its width may well be reduced markedly, though this is true for all V-twins. The crankshaft is short and rigid, and the two connecting rods are mounted side by side on the same crankpin. The power strokes are not uniformly distanced but follow every 450 degrees—270 degrees—450 degrees. Diminishing the angle between the cylinders improves the longitudinal compactness of the engine but degrades the balance.

In this BMW boxer twin (below) the forces of inertia of both the first and second order are balanced. The two cylinders are not coaxial, however, which generates perceptible vibrations. BMW eliminates them with a balance shaft.



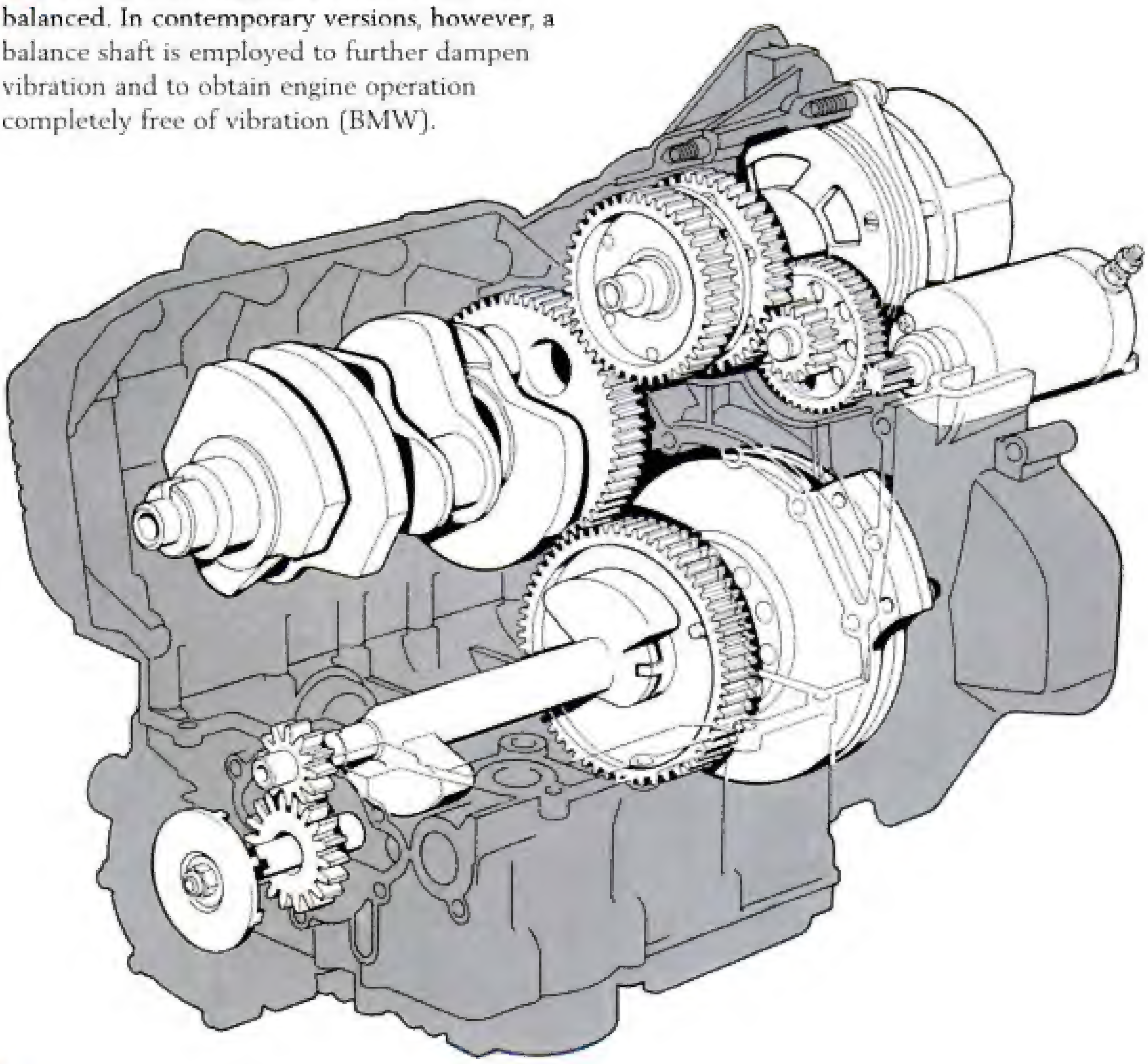
Two methods are employed to reduce the vibrations in V-twins. The first is the "classical" solution and calls for the use of an auxiliary crankshaft (less often two). The second adopts a crankshaft fitted with not one but two staggered crankpins; as is obvious, this presents advantages in terms of construction simplicity and containment of costs, but it is less suitable for use on high-performance engines since the crankshaft is less rigid and strong, given the diameter of the pins. (The crankpins are separated by a narrow unsupported central flywheel.) Neither of these solutions achieves an equal distance between the power strokes.

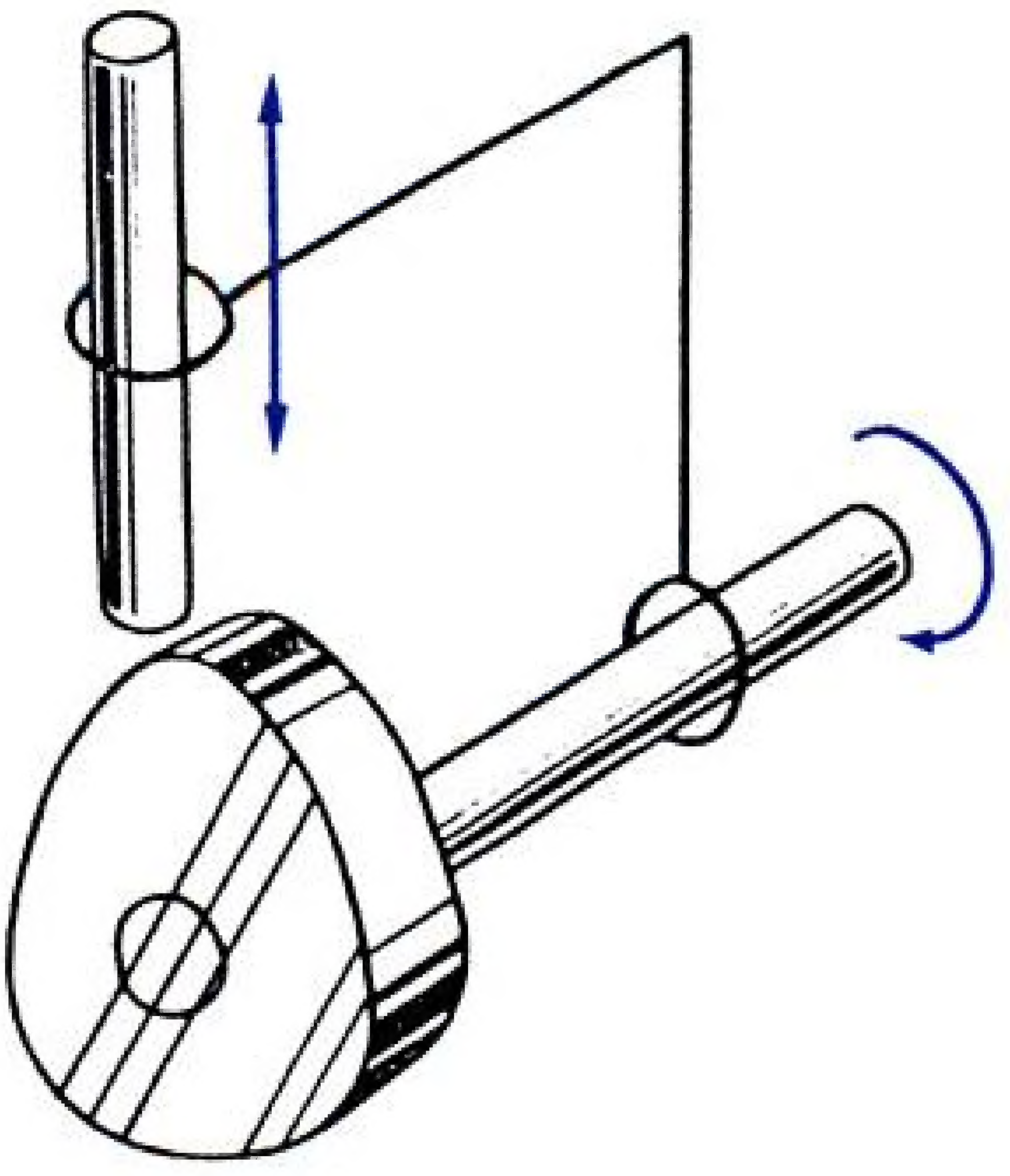
Boxer twins form a category of their own. BMW is the best known proponent of this arrangement, which features a longitudinal axis of the crankshaft and horizontally opposed cylinders that protrude from either side of the crankcase. With this arrangement, the balance is nearly perfect, with very low vibration levels and equidistant engine power strokes. This arrangement is also well suited to air cooling, since the heads and the cylinders are fully exposed to the airstream. The crankshaft rests on two supports and is fitted with two crankpins arranged at 180 degrees. The side-to-side bulk is considerable, while the length and vertical heights are well contained. This arrangement requires an automobile-type transmission, with separate gears and shaft-driven final drives.

Three and Four Cylinders

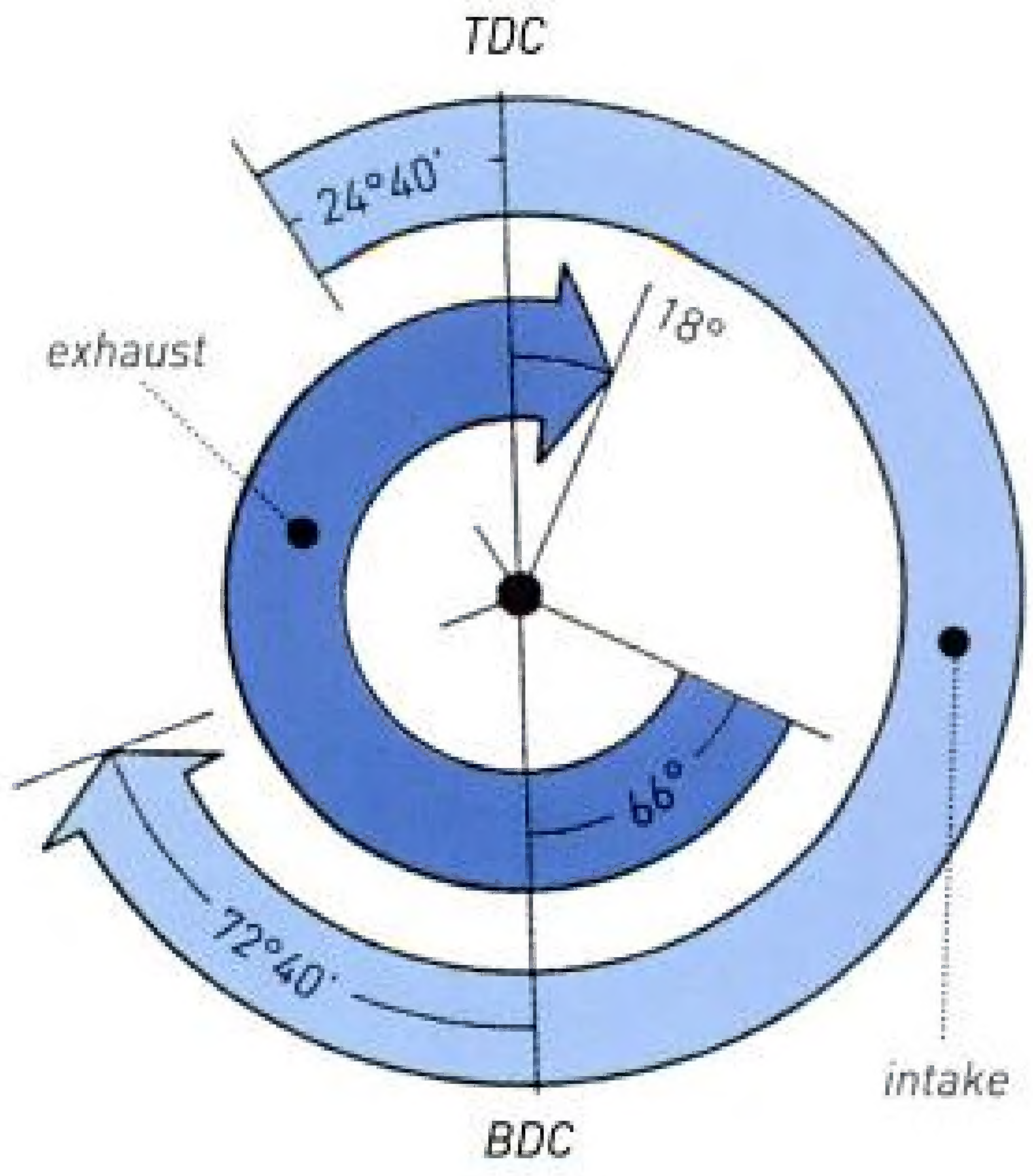
Motorcycles featuring three-cylinder engines have been manufactured several times over the history of the motorcycle, and while not built in great

Three-cylinder engines are inherently well balanced. In contemporary versions, however, a balance shaft is employed to further dampen vibration and to obtain engine operation completely free of vibration (BMW).



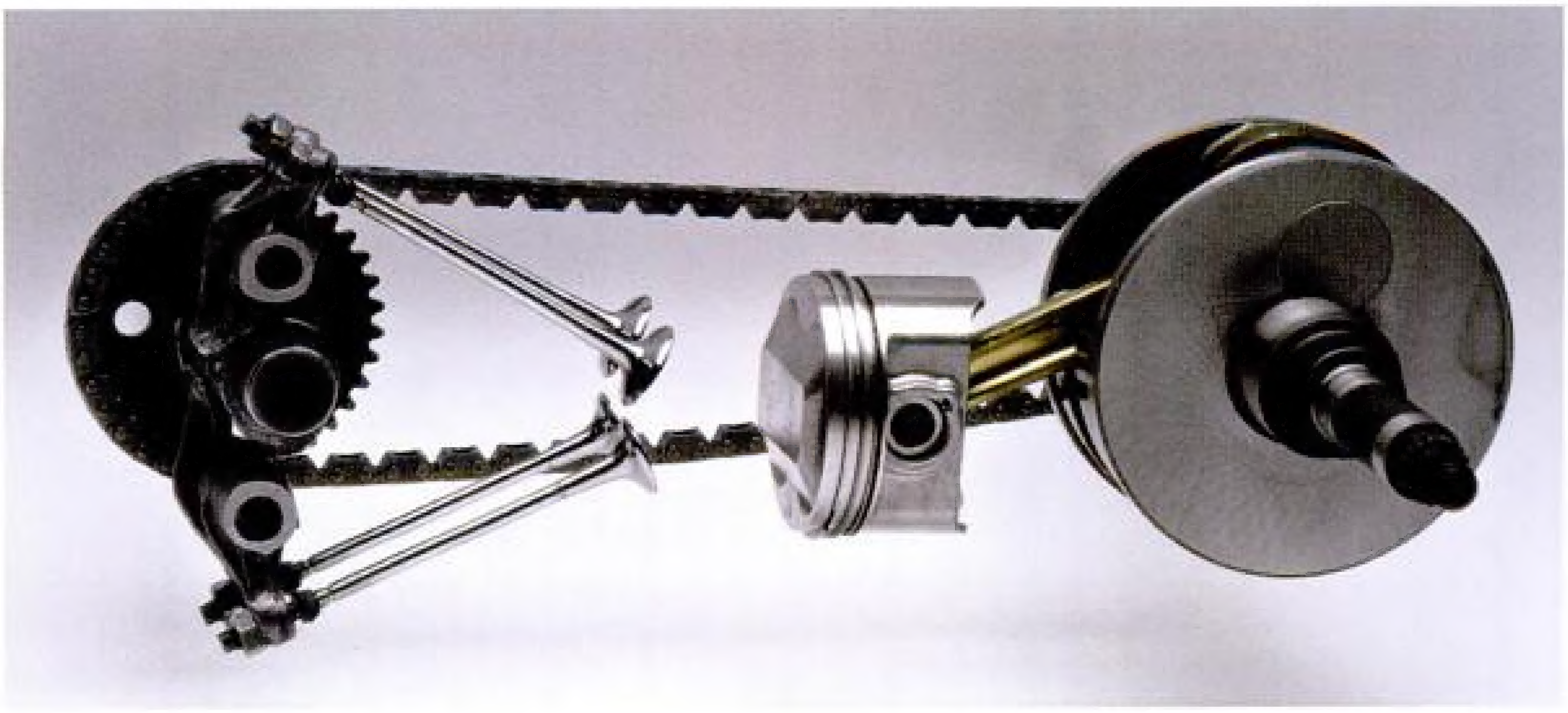


This drawing illustrates the way the camshaft lobe transforms rotating movement into the linear movement of the rocker arm (Honda).

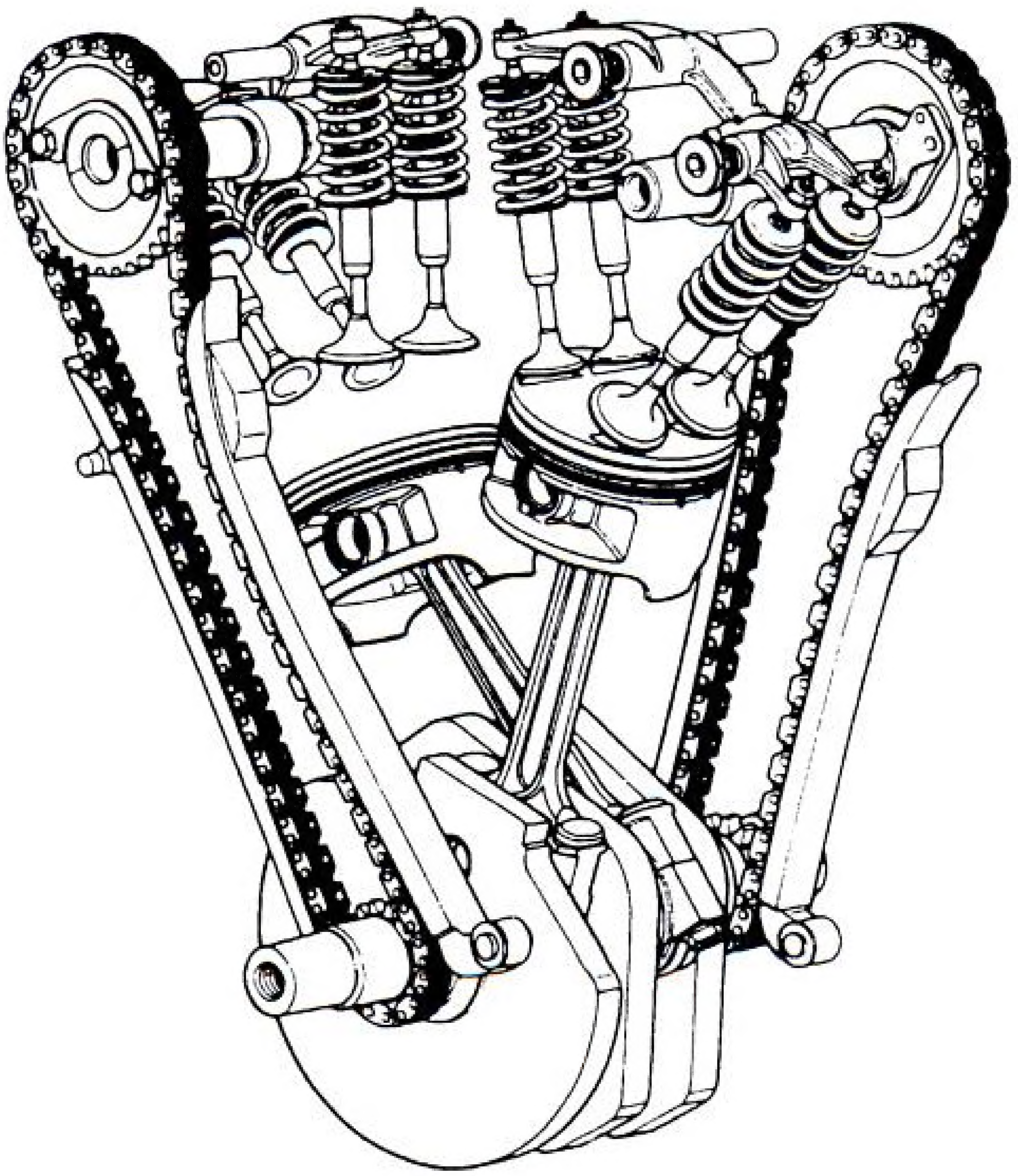


A typical valve timing diagram for a four-stroke engine: In this case, the exhaust has a duration of 264 degrees and an intake of 277 degrees 20 minutes (Alfa Romeo).

the intake valve already rising from its seat when the force exercised by the piston becomes considerable, in the first part of the stroke, from TDC to BDC, it must begin to open before the piston reaches TDC at the end of the exhaust stroke. The same happens with its closing, which must end considerably later than BDC at the end of the intake stroke. The situation is absolutely the same for the exhaust valve. Thus, the beginning of the opening of the valves and the end of their closing do not coincide with the dead points, which means the phases of intake and exhaust are not confined to their relative strokes. Even the compression stroke begins with a certain delay with regard to BDC, meaning precisely when the intake valve comes in contact with its seat, and thus it does not coincide with the compression stroke but has a smaller angular duration. The same holds true for the combustion phase



Many engines have only a single overhead camshaft, almost always chain-driven. In the example here, the valves are activated by two-arm rocker arms (Aprilia).



This single-camshaft V-twin has two silent chains, one for each head and thus for each camshaft (Suzuki).

and stroke. (The exhaust valve begins to open before BDC is reached.)
This situation is very advantageous in terms of performance since it makes it possible to best exploit the energy of the gas column that enters and exits the cylinder and the waves of pressure that travel inside the ports.

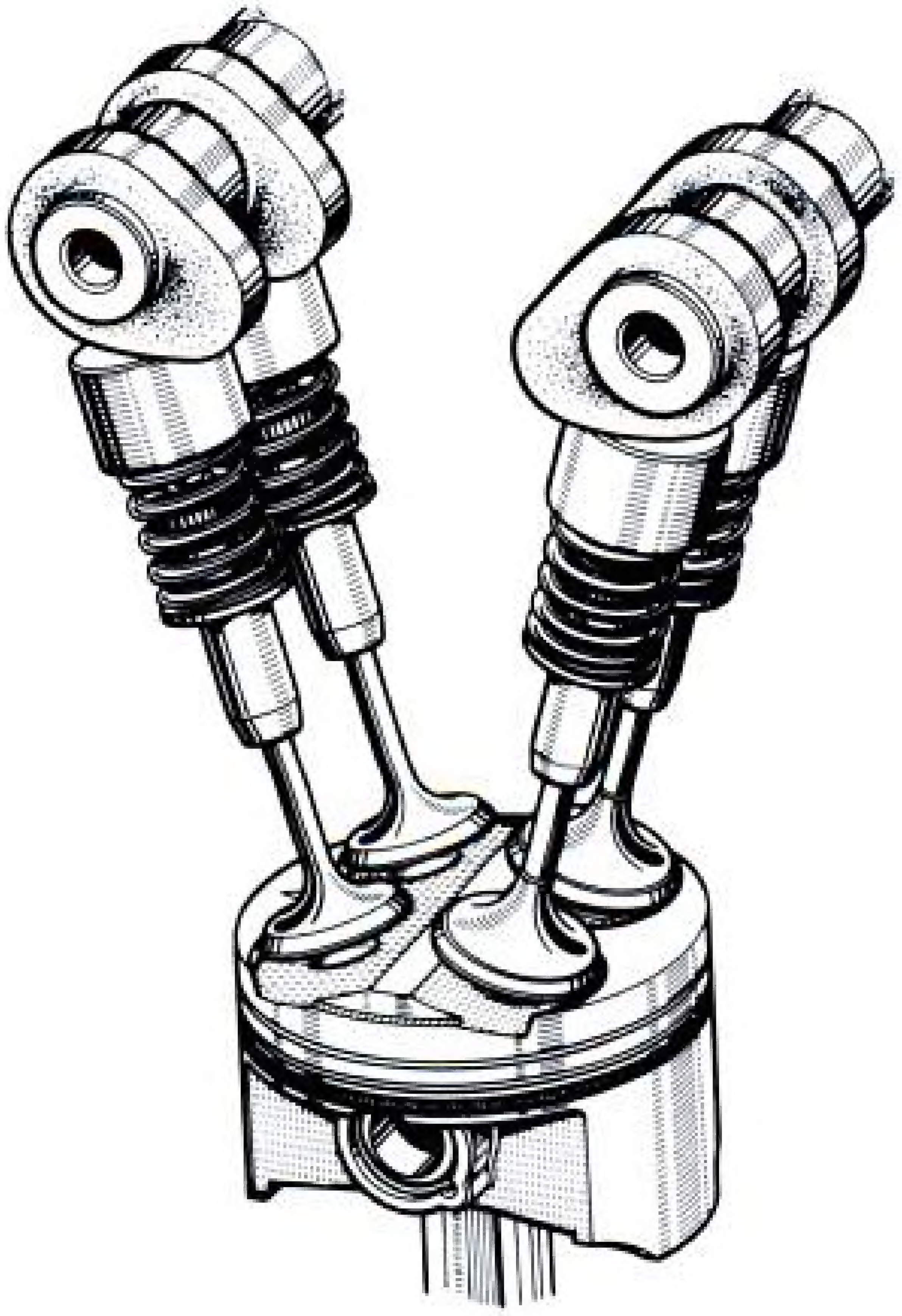
Inertia of Gases and Pressure Waves
The intake valve begins to move from its seat well before the piston has arrived at TDC at the end of the exhaust stroke. The exhaust valve finishes closing after the piston has moved past TDC. This means that for a certain period, during TDC at the end of the exhaust stroke, both valves are partially open. This is known as valve overlap. This is advantageous in terms of scavenging the combustion chamber: The drawing action exercised by the exhaust contributes to putting in movement the fresh air/fuel mixture, which then enters the cylinder and "sweeps" the chamber, freeing it of burnt gases. The intake phase begins even before the piston has begun to descend from TDC to BDC. Obviously this functions best only when the engine is running at certain speeds.

The intake valve does not fully close until a good while after the piston has passed BDC. Because of their inertia, the fresh gases continue to enter the cylinder even after the piston has changed the direction of its movement and has begun to rise toward TDC.
It is clear that, in terms of refilling the cylinder, it is best if the valve finishes closing precisely when the gas column has stopped arriving. Also in this case, a certain delay in closing provides the

best results in terms of performance, at a certain speed of engine rotation. The exhaust valve begins to open considerably before BDC. This is advantageous since the burnt gases begin to pour into the exhaust port thanks to their pressure, exiting in great quantity even before the piston has reached BDC; as a consequence, when the piston rises toward TDC, it has less work to do to expel the remaining exhaust gases. The advanced opening of the exhaust valve causes a reduction in the effective length of the combustion phase, but it must be pointed out that in the last part of the combustion stroke the gases have already done most of their work on the crown of the piston; the pressure in the cylinder is by then somewhat low and furthermore the angle between the connecting rod and the crank web on the crankshaft is disadvantageous.

Thus, very little efficiency is lost. Aside from the inertia of the gas column, modern high-performance engines fully exploit the pulsating phenomena that take place inside the intake and exhaust systems. Clearly, if a strong positive wave arrives just when the intake valve is nearly finished closing, the refilling improves. (It is as though a true "fluid piston" pushed more of the mixture into the cylinder.)

During the exhaust phase, it is important for a wave of negative pressure to reach the valve during the period of valve overlap, just when it is about to close. As for exploiting pressure waves to increase the volumetric output of the engine, it is clear that, with a certain amount of anticipation in the opening of valves and delay in their closing, the best results (for every given configuration of the intake and exhaust systems) will occur at a certain speed of engine rotation.



By far the most common arrangement in high-performance engines is to have bucket tappets (the cylindrical lifters) between the camshaft lobes and the four valves of each cylinder (Suzuki).

Timing and Performance

Advancing and retarding the opening and closing of the valves in relation to the dead points of the cylinder constitutes valvetrain timing, which is usually expressed in degrees of crankshaft rotation. Timing that involves greater advancing and retarding makes it possible to obtain improved performance at high engine rpm; such timing is typical for sportbike engines that have very high specific power but not a strong power range at low and medium speeds. On the contrary, modest advancing and retarding are suitable for lower performance engines that do not rotate at high rpm and that provide modest performance in relation to their displacement (but that offer power over a broad rpm range).
Valve timing can be expressed graphically with a circular or spiral

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